

DEMONSTRATION EXPERIMENTS OF RESSOX USING “MICHIBIKI”

Toshiaki Iwata, Kojiro Saito, Kumiko Machita, Takashi Matsuzawa
National Institute of Advanced Industrial Science and Technology (AIST)
1-1-1 Umezono, Tsukuba Central 2, Tsukuba, Ibaraki 305-8568, Japan
TEL: +81-29-861-5706, FAX: +81-29-861-5709
totty.iwata@aist.go.jp

Takashi Kawauchi
Mitsubishi Space Software Co. Ltd., Japan

Yoshiharu Fukuhara
Space Engineering Development Co. Ltd., Japan

Tamotsu Hiroshima, Kazuo Tokita
Cosmo Research Corporation, Japan

Tamaki Takahashi, Satoshi Horiuchi
NEC Corporation, Japan

Yasuhiro Takahashi
**National Institute of Information and Communications Technology (NICT),
Japan**

Abstract

The first Quasi-Zenith Satellite (QZS) of Japan named “Michibiki” was launched on September 11, 2010. After the first three months of initial functional verification tests, demonstration experiments were started on December 13, 2010. Three kinds of demonstration experiments using Michibiki have been planned for RESSOX (Remote Synchronization System of the Onboard Crystal Oscillator): (1) experiments without onboard voltage-controlled oven-compensated controlled crystal oscillator (VCOCXO) control of Experiment One (Exploratory Experiments), (2) experiments with onboard VCOCXO control of Experiment One, and (3) experiments with onboard VCOCXO control of Experiment Two. In Experiment One, the RESSOX control signal that includes information of the standard time is sent from ground stations and the onboard crystal oscillators of QZS are controlled to synchronize the arrival of the RESSOX control signal. The RESSOX control signal is similar to such time calibration signals as WWV or JJY, but the delay is compensated. In Experiment Two, on the basis of the results of time comparison between the onboard VCOCXO and the ground standard time conducted by the National Institute of Information and Communications Technology (NICT), the voltage applied to the onboard VCOCXO is calculated at the ground station and transmitted to QZS to control VCOCXO. Demonstration experiments of (2) and (3) were performed in March, May, July, September, and November 2011, and will be performed in January 2012 for one week each. At the moment, the feedback control of Experiment One has been successfully confirmed; however, the synchronization error is approximately 1200 ns peak-to-peak. In Experiment Two, the synchronization error in the time comparison experiment of NICT is less than 0.3 ns for six days, which means that the performance is comparable to that of hydrogen

masers. In this paper, the experimental results obtained so far by the demonstration experiments are presented and discussed.

I. INTRODUCTION

The development of the Quasi-Zenith Satellite System (QZSS) as a Japanese space project has been ongoing since 2003, and its mission is navigation and/or positioning [1]. Its constellation consists of at least three satellites orbiting on inclined orbital planes with a geosynchronous period. The first QZS, named “Michibiki,” was launched on September 11, 2010. The QZSS utilizes a high inclined orbit because of the high visibility over high-latitude regions. In the case of the QZSS, at least one satellite is highly visible near the zenith at any time from Japan. Therefore, users in Japan can always receive navigation signals from at least one of the QZSSs near the zenith.

In general, a global navigation satellite system (GNSS), such as the GPS of the U.S.A., GLONASS of Russia, GALILEO of Europe, and COMPASS of China, is equipped with onboard atomic frequency standards that are used as time reference. This is because: (1) atomic clocks have good long-term stability, (2) the orbit of satellites makes monitoring from one ground station impossible, (3) these satellite systems are used for military missions and are therefore expected to operate even if ground stations are destroyed, and (4) these systems consist of many satellites, making the control of each satellite with many antennae difficult. However, onboard atomic clocks have the following disadvantages: they are bulky, expensive to manufacture and launch, and power-demanding. Moreover, they are one of the main factors contributing to the reduction of satellite lifetime.

The following issues have been taken into consideration in the design of the QZSS as a civilian navigation system: (1) some crystal oscillators have better short-term stability than atomic clocks [2], (2) 24-hour control with one station is possible if the location of the control station is appropriate, for example, Okinawa, Japan, and (3) the number of satellites is assumed to be only three. Given these considerations, it is reasonable to develop the remote synchronization system of the onboard crystal oscillator (RESSOX), which does not require onboard atomic clocks. In the case of RESSOX, modification of the control algorithm after launch is easy because it is basically a ground technology. The target synchronization accuracy of RESSOX is set at 10 ns and the target stability is 1×10^{-13} at 100,000 s. These targets were determined on the basis of the synchronization performance between GPS-Time (GPST) and UTC (USNO) [3] and the long-term stability performance of onboard cesium atomic clocks [4].

Two kinds of experiments are scheduled as RESSOX operations: Experiment One and Experiment Two. In Experiment One, the RESSOX control signal that includes information of the standard time is sent from ground stations and the onboard voltage-controlled oven-compensated crystal oscillator (VCOCXO) of Michibiki is controlled to synchronize the arrival of the RESSOX control signal. The RESSOX control signal is similar to such time calibration signals as WWV or JJY, but the delay is compensated. In Experiment Two, on the basis of the results of time comparison between the onboard VCOCXO and the ground standard time conducted by the National Institute of Information and Communications Technology (NICT), the voltage applied to the onboard VCOCXO is calculated at the ground station and transmitted to Michibiki to control the onboard VCOCXO.

RESSOX ground experiments and computer simulations have been conducted since 2003. The results of primary research are detailed in our previous papers [5-11]. We confirmed the RESSOX algorithm using computer simulation, ground hardware simulator, and geostationary satellites for Experiment One [5-10]. We also discussed the discontinuity of orbit estimation/forecast values used in Experiment One

and the time delay of voltage command for Experiment Two [11].

After the first three months of initial functional verification tests [12], demonstration experiments were started on December 13, 2010. Three kinds of demonstration experiments using Michibiki have been planned: (1) experiments without onboard VCOCXO control of Experiment One (Exploratory Experiments), (2) experiments with onboard VCOCXO control of Experiment One, and (3) experiments with onboard VCOCXO control of Experiment Two. Demonstration experiments of onboard VCOCXO control were performed in March, May, July, September, and November 2011, and will be performed in January 2012 for one week each. In this paper, the experimental results obtained so far by the demonstration experiments are presented and discussed.

In a practical sense, the QZSS is loaded with two rubidium atomic standards. RESSOX is used in the experiments to examine their use in future QZSSs.

II. RESSOX OVERVIEW

Two kinds of RESSOX experiments, Experiment One and Experiment Two, have been designed.

EXPERIMENT ONE

In order to realize Experiment One, it is necessary to identify the error and delay of the RESSOX control signal and the feedback mechanism by estimating the delay of the onboard VCOCXO at the Time Management Stations (TMSs), which are ground stations located at NICT sites (Koganei, Tokyo and Onna, Okinawa). The former is related to the estimation of error and delay using models, and is considered to be a feed-forward control (FF). The latter is an error adjustment system that uses the pseudoranges measured with the navigation signals of the QZSS and the estimated pseudoranges, and is considered to be a feedback control (FB).

Figure 1 shows the system diagram of Experiment One using Michibiki. Experiment One uses JAXA assets, NICT assets, and our own assets. GPST obtained by GPS synchronizer or QZSS-Time 1 (QZSST1) that is based on UTC(NICT) is used as standard time. RESSOX control signal transmitter (RCST) advances the time of the RESSOX control signal to compensate the delay during transmission between GPST or QZSST1 and VCOCXO onboard Michibiki. Time information of the RESSOX control signal is modulated with a pseudonoise (PN) code also by RCST at TMS, up-converted to 14.43453 GHz (Ku-band) by the up-converter, and transmitted from the Ku-band antenna of TMS to Michibiki ceaselessly, except during the approximately 35-minute communication interruptions (CIs) twice a day. At Michibiki, the RESSOX control signal is received by the Ku-band antenna, down-converted, and demodulated for comparison with that of the onboard VCOCXO by the time comparison unit (TCU) of NICT. The time-difference information (PN-code phase difference) between the arrived RESSOX control signal and VCOCXO time is transferred to the navigation onboard computer (NOC) of JAXA. Then, NOC generates the control command (voltage to be applied) for VCOCXO through an appropriate control algorithm. On Michibiki, the navigation signals of L1-, L2-, and L5-bands are generated by the L-band signal transmission subsystem (LTS) using the VCOCXO time as the reference clock. At TMS, navigation signals are received by the L-band antenna and transmitted to the QZSS/GPS receiver (QZSSREC) for RESSOX. The QZSSREC compares time information in Michibiki's navigation signals with GPST or QZSST1 and outputs the pseudoranges to the RESSOX controller (RC). The pseudoranges are used to calculate the time to be adjusted of the RESSOX control signal. RC at TMS controls RCST using both the delay models (feed-forward control) and the time to be adjusted (feedback control). To monitor the performance of RESSOX, the results of the time comparison conducted by NICT and JAXA's clock offset included in the orbit estimation/forecast values

are collected by RC.

In actual operation, three delay estimation methods have been prepared by JAXA. They are the three-minute orbit estimation/forecast values, the seven-day continuous delay estimation using models, and the delay estimation using L1C/A navigation message. To realize continuous RESOX operation, use of the three-minute orbit estimation/forecast values is indispensable. In this study, we focus on the processing of the three-minute orbit estimation/forecast values.

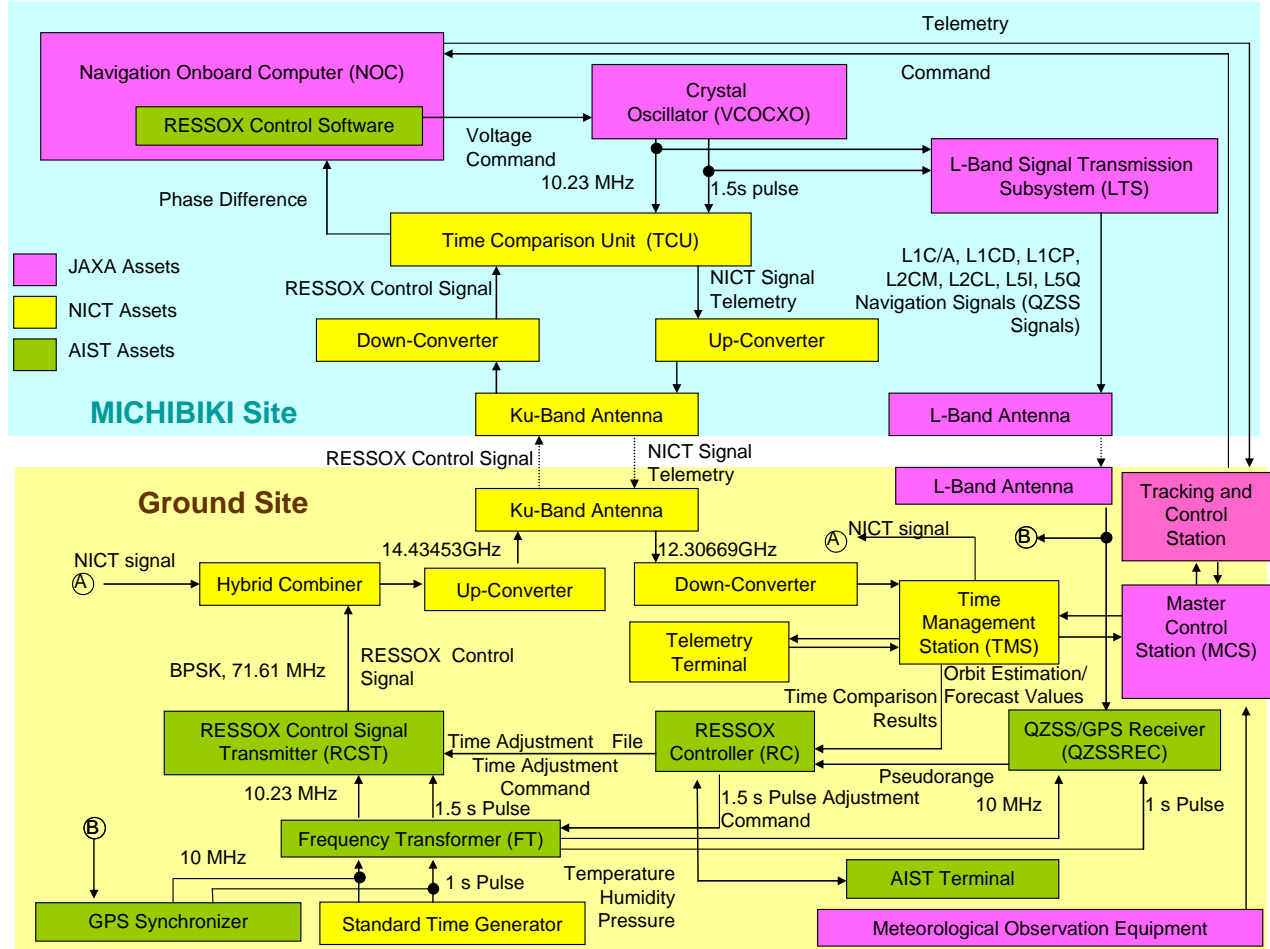


Figure 1. System diagram of Experiment One using Michibiki.

In the case of the three-minute orbit estimation/forecast values, every 30 s, RC receives orbit estimation and forecast values in the International Terrestrial Reference Frame (ITRF) and clock offset in GPST for a duration of three minutes, as shown in Figure 2. The data discontinuity that occurs every 30 s is an issue that needs to be resolved [11].

EXPERIMENT TWO

To realize Experiment Two, the results of the time comparison between the onboard VCOCXO and QZSST1, conducted by NICT, are indispensable. The voltage to be applied to VCOCXO is calculated on the basis of the results obtained at TMS and up-linked every 1.5 s ceaselessly, except during the 35-minute CIs twice a day.

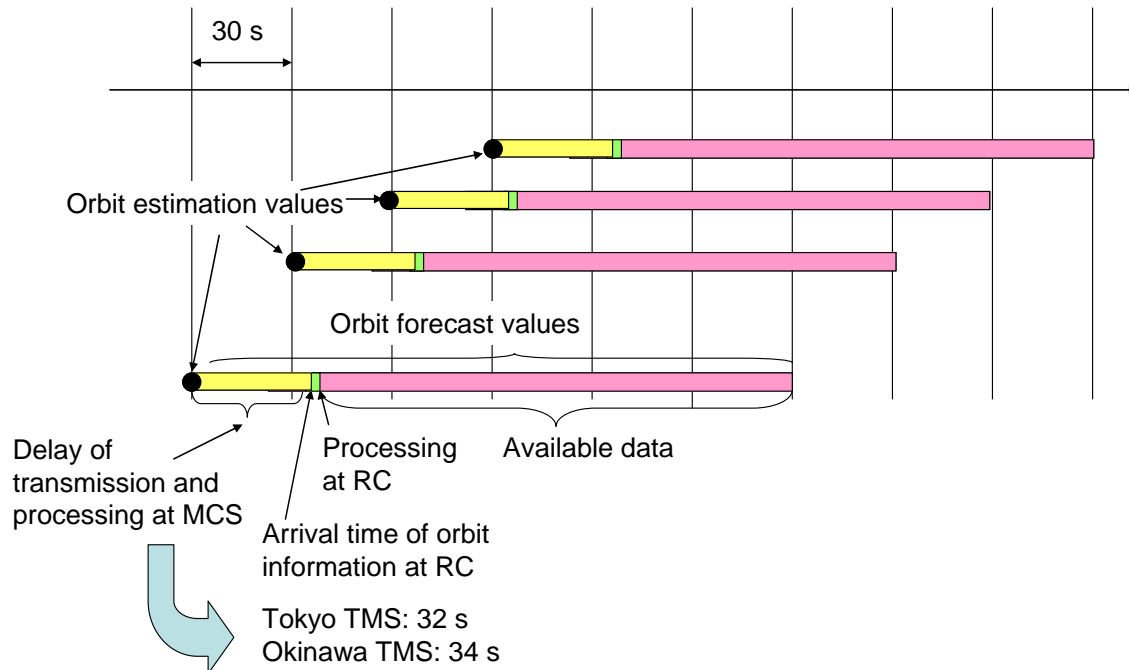


Figure 2. Processing of three-minute orbit estimation/forecast values.

Figure 3 shows the system diagram of Experiment Two using Michibiki. Experiment Two also uses JAXA assets and NICT assets, and RC at TMS and RESSOX control software in NOC, which are AIST assets.

The time delay of the voltage command from TMS to Michibiki is the main issue that must be resolved to realize this architecture [11]. The delay is assumed to be within 20 s; it is actually 9 s at Tokyo TMS and 12 s at Okinawa TMS. Command processing and delay estimation are shown in Figure 4. An original voltage command that has one integer digit and eight decimal digits, such as 5.12345678 (V), is sent to the Master Control Station (MCS) as ASCII characters from RC. Then, the command data packet that is constructed by a 944-bit binary code is sent back from MCS to RC. MCS checks the voltage command to determine whether it is acceptable or not, and if it is not acceptable, the data packet is not sent. Using the data packet, RCST constructs the command, combining it with header and dummy packets. Then, the actual voltage command is uplinked from TMS to Michibiki. At Michibiki, TCU decodes the command and sends it to NOC. Finally, NOC provides the control voltage for VCOCXO.

III. DEMONSTRATION EXPERIMENTS

SCHEDULE AND PLANS

Demonstration experiments of RESSOX have been conducted since December 13, 2010 and will be continued until the end of January 2012. During this period, six one-week demonstration experiments with onboard VCOCXO control are planned, whereas exploratory experiments without VCOCXO control will be conducted in other periods.

In the case of experiments with VCOCXO control, we stay at TMSs where the RESSOX ground apparatuses are located in order to respond to various situations, such as emergency shutdown. Experiments One and Two are conducted in various conditions and long-term stability is investigated.

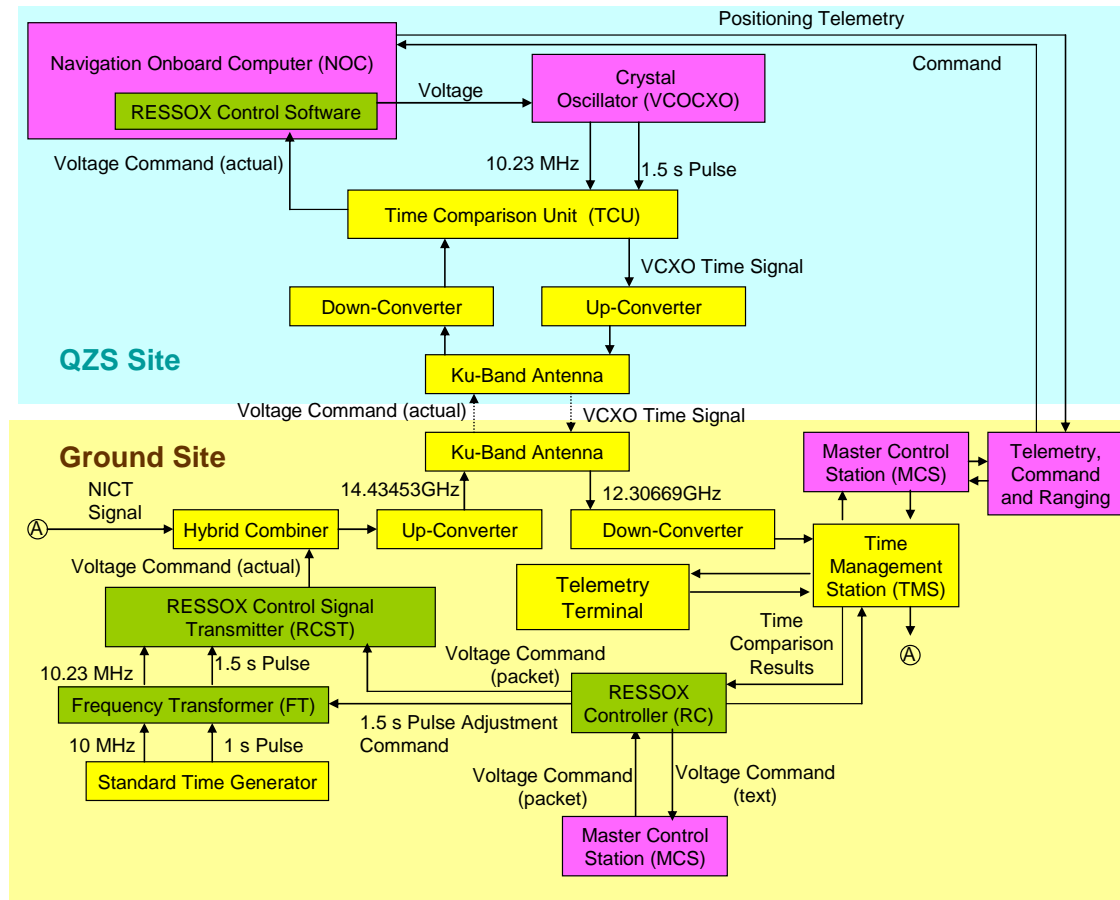


Figure 3. System diagram of Experiment Two using Michibiki.

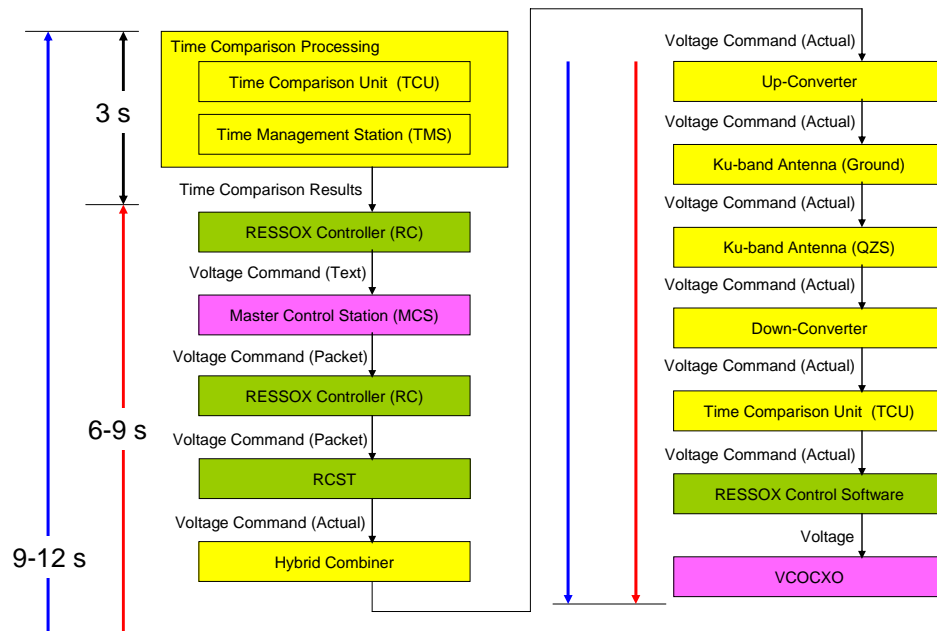


Figure 4. Command processing of Experiment Two and delay estimation.

In the case of exploratory experiments, using uplink with Ku-band and navigation signals, we investigate the relativity effects and the model of tropospheric delay.

So far, experiments with onboard VCOCXO control were conducted from March 3 to 12, May 15 to 21, July 16 to 22, September 17 to 23, and October 29 to November 4, 2011, and there are plans to conduct such experiments from January 22 to 27, 2012. In March, operation checks of Experiments One and Two were mainly conducted. In May, advanced operation checks of Experiments One and Two were conducted. In July, long-term performance of Experiment Two was investigated. In September, various performances of Experiments One and Two were examined. In November, the performance of Experiment One will be checked (the results are not included in this paper). In January, switch-over experiments between Okinawa and Koganei will be conducted.

RESULTS OF EXPLORATORY EXPERIMENTS

In the case of exploratory experiments, two time comparison results were compared. They were (1) the time difference between onboard clock time and arriving RESSOX control signal generated by GPST, and (2) clock offset measured by JAXA using monitoring station information (time difference between onboard clock time and GPST, relativity effects are included). The results are shown in Figure 5. In the case of (1), RESSOX control signal was generated only by orbit estimation/forecast values, that is, relativity effects and other delay origins were not considered.

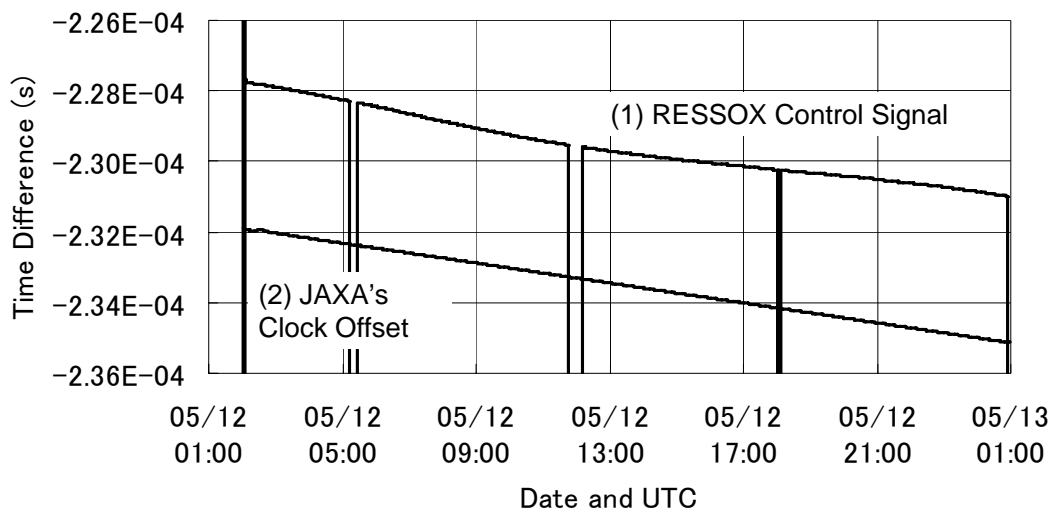


Figure 5. Results of exploratory experiments. Comparison between RESSOX control signal and JAXA's clock offset.

The difference between (1) and (2) can be explained by mainly relativity effects and tropospheric delay shown as Figs. 6 and 7. The final residual error was obtained as shown in Figure 8 and the fluctuation was within 30 ns, which might have been caused by the ionospheric delay and the orbit error.

RESULTS OF EXPERIMENT ONE

In the case of Experiment One, relativity effects have not been taken into consideration so far. The results were evaluated relative to JAXA's clock offset and NICT's time comparison results. The experimental results in March exhibited peak-to-peak synchronization errors of 800 ns with NICT's time comparison results and 1200 ns with JAXA's clock offset, as shown in Figure 9. As the elevation angle

of Michibiki was small from around 6:00 to 13:00 on March 7, QZS signals for FB were not received. Therefore, only FF was executed.

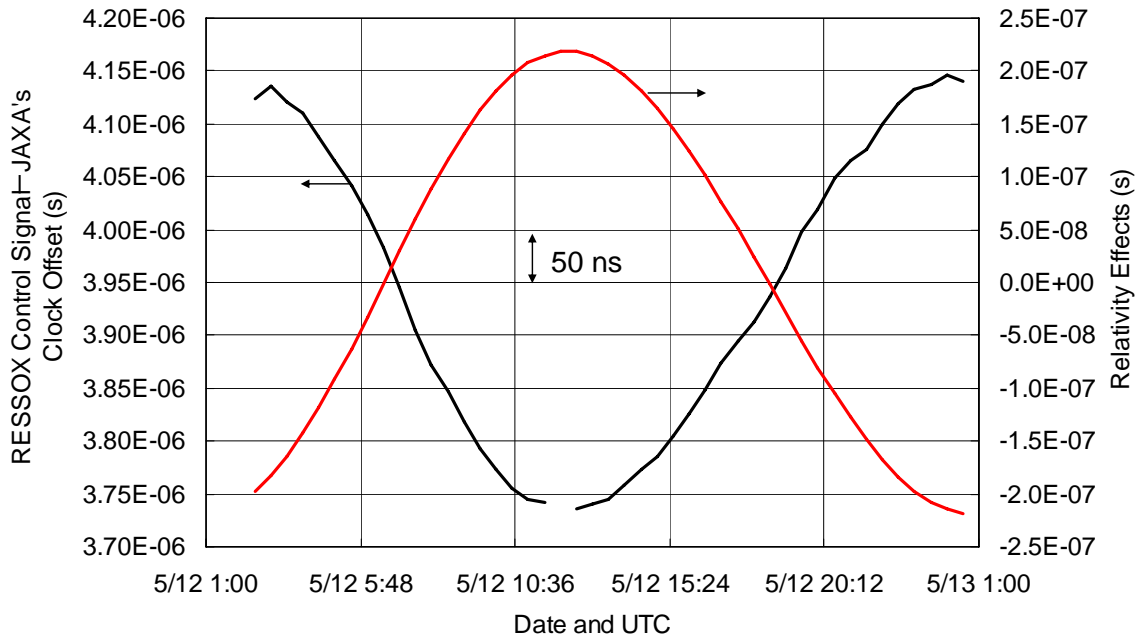


Figure 6. Results of exploratory experiments. Relativity effects are taken into consideration.

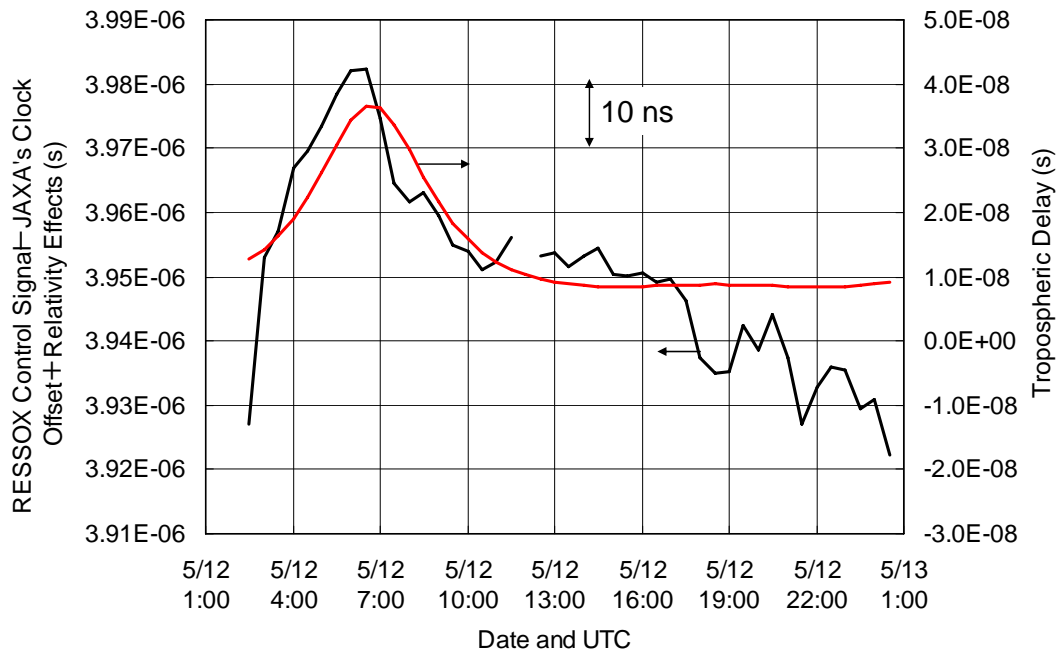


Figure 7. Results of exploratory experiments. Tropospheric delay is taken into consideration.

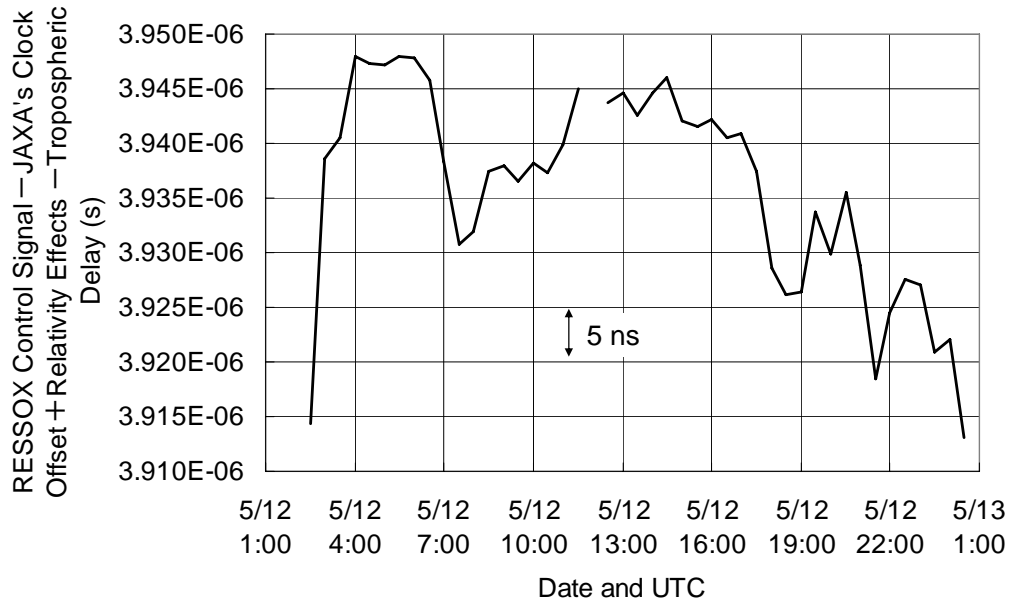


Figure 8. Final results of exploratory experiments.

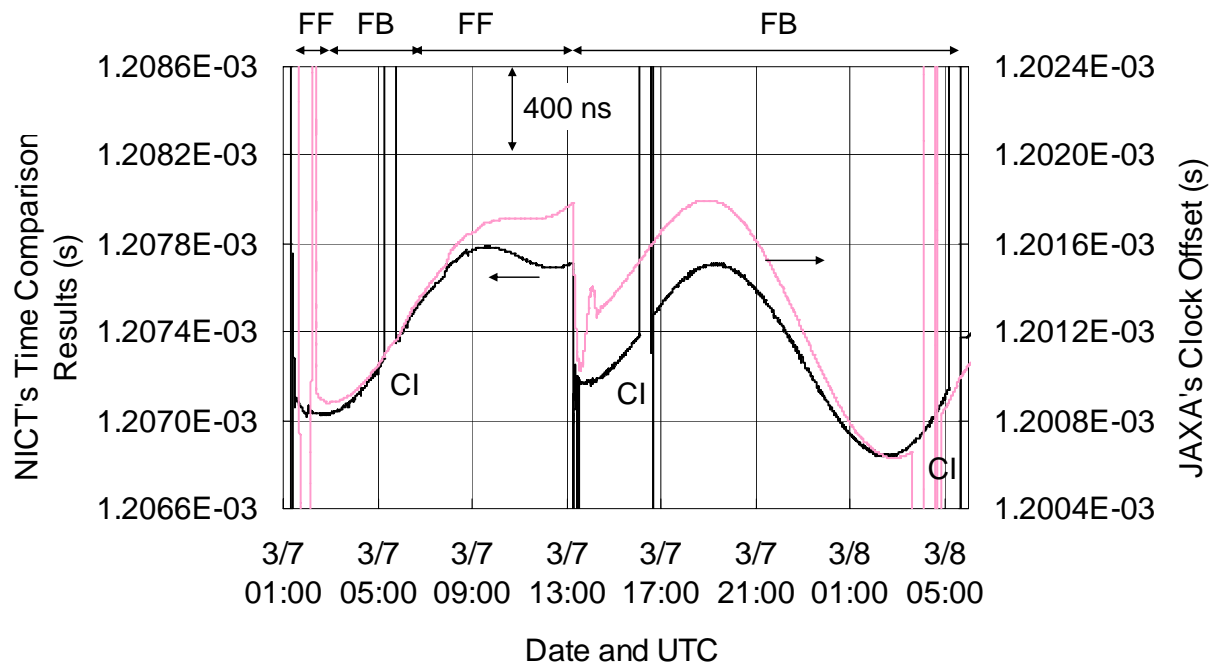


Figure 9. Results of Experiment One conducted in March.

The reasons for the error were estimated to be the disagreement of signal transmission timing and the error included in FB. However, as neither NICT's time comparison results nor JAXA's clock offset guaranteed correction at that moment, identification of the origin of the error was difficult. The error included in FB, which is the difference between the measured pseudorange of the L1C/A signal obtained by QZSSREC and the pseudorange estimated by JAXA's orbit estimation/forecast values, was approximately 500 ns peak-to-peak, as shown in Figure 10.

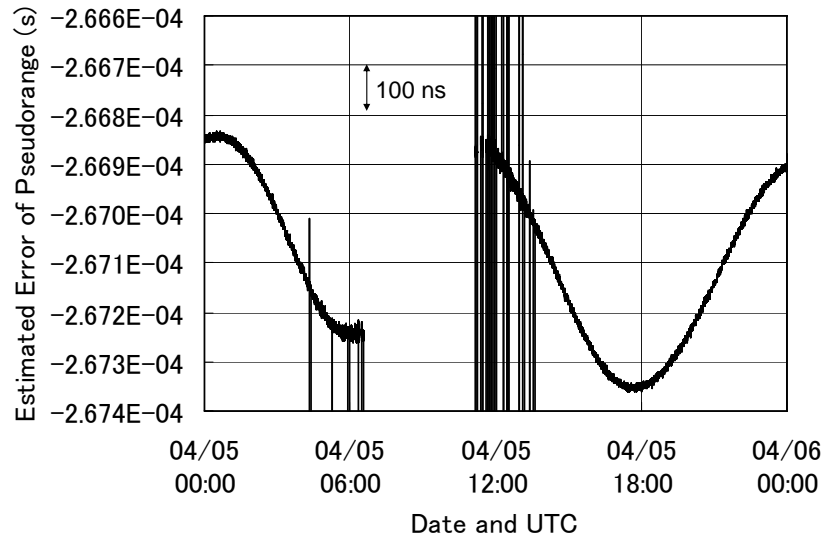


Figure 10. Estimated error of pseudorange of L1C/A signal used in FB.

The difference of 600 ns peak-to-peak between NICT's time comparison results and JAXA's clock offset was mainly generated by relativity effects. When FB was conducted, control of the onboard VCOCXO fluctuated by about ± 10 ns and control voltage also fluctuated, as shown in Figure 11.

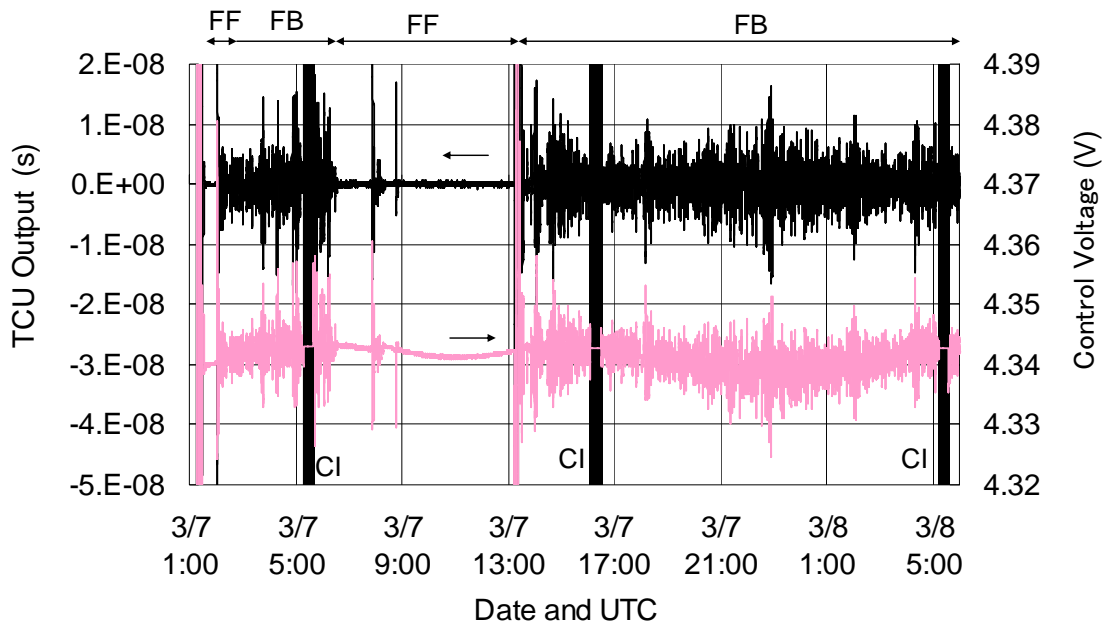


Figure 11. TCU output and control voltage of Experiment One conducted in March.

The experimental results in May exhibited peak-to-peak synchronization errors of 1800 ns with NICT's time comparison results and 1200 ns with JAXA's clock offset, as shown in Figure 12. Because the direction of the antenna of L1 navigation signals was changed, L1C/A signals were received for 24 hours and FB was conducted for 24 hours. However, the error was larger than that of experiments conducted in March and the origin was unknown. Moreover, a malfunction occurred, which involved tracking error of the RESSOX control signal immediately before CI. This malfunction was solved in September. However, no new results have been obtained so far.

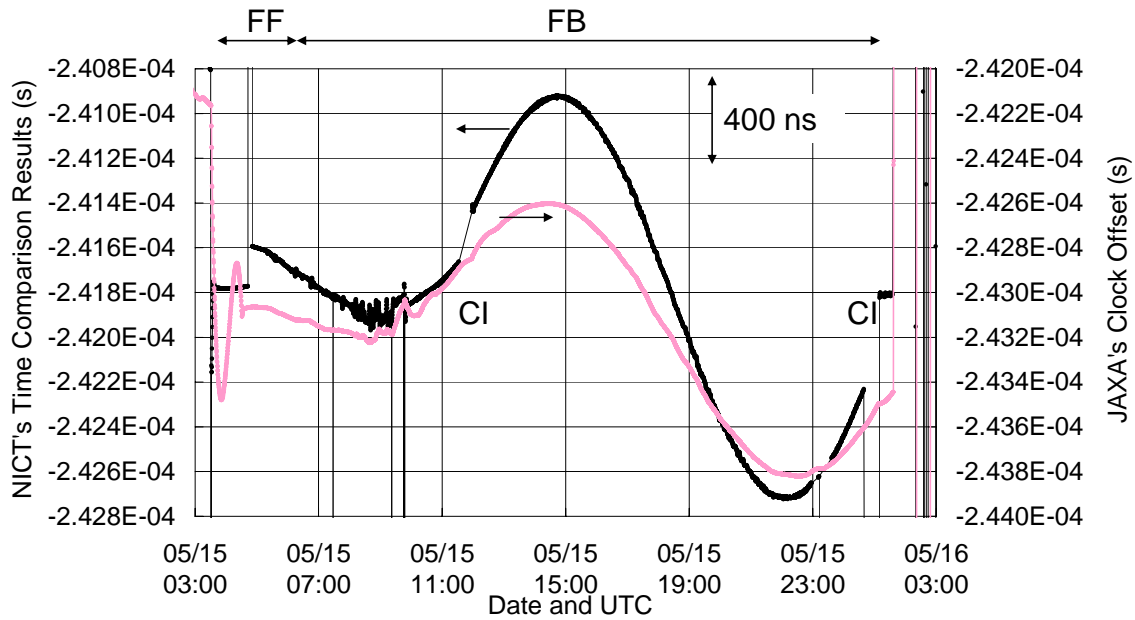


Figure 12. Results of Experiment One conducted in May.

RESULTS OF EXPERIMENT TWO

In the case of Experiment Two, if NICT's time comparison results are correct, synchronization within ± 0.3 ns is obtained. In March, the synchronization was achieved to have some offset that was easy to realize (1.253756×10^{-3} s), as shown as Figure 13. The value of JAXA's clock offset was estimated to be generated by mainly relativity effects. Figure 14 shows the control voltage during experiments. Even though the experiment was conducted for a short period, the control voltage change was rather large. This means that VCOCXO requires frequent control.

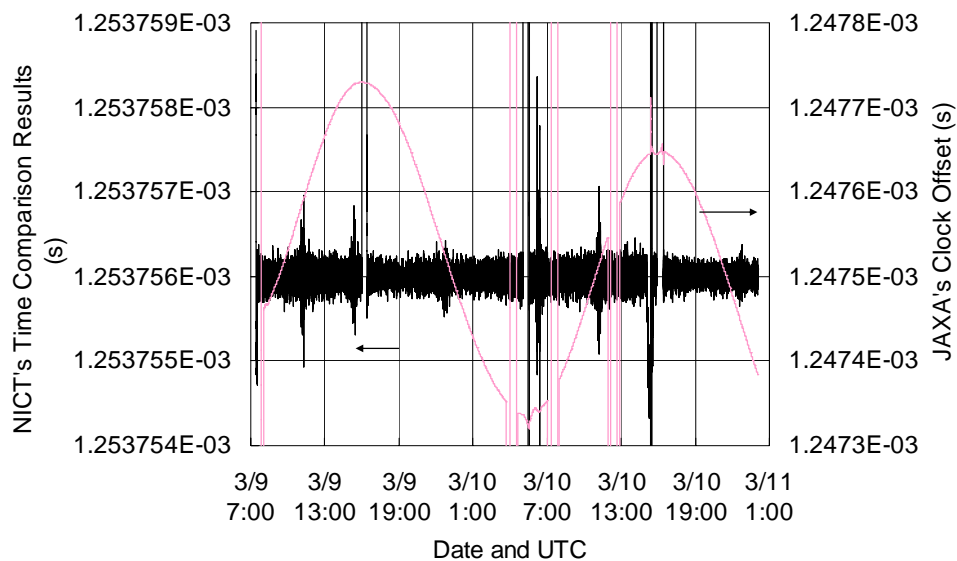


Figure 13. Results of Experiment Two conducted in March.

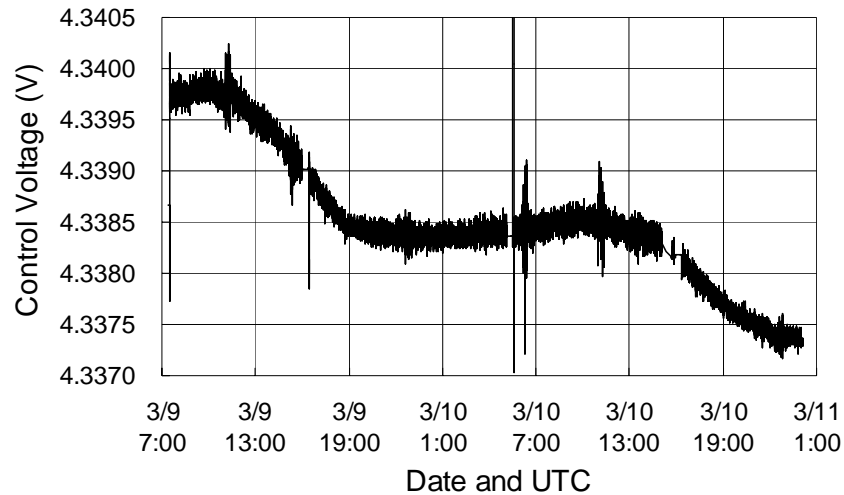


Figure 14. Control voltage of Experiment One conducted in March.

In May, NICT's time comparison results were controlled to zero and relativity was added to NICT's time comparison results, as shown in Figure 15. As a result, NICT's time comparison results showed a sinusoidal curve of 200 ns amplitude and a 24-hour period. However, JAXA's time offset revealed an unaccountable behaviour. This was solved in September.

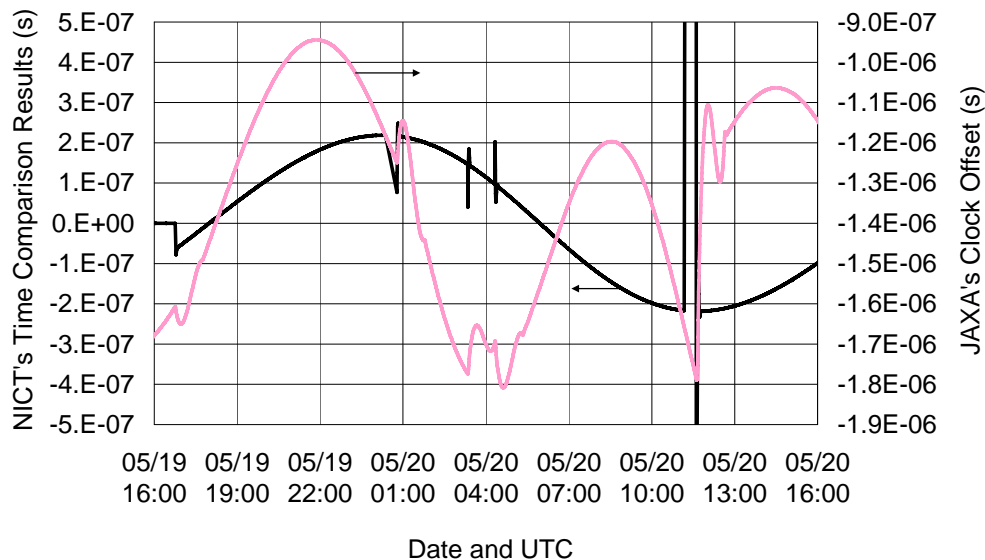


Figure 15. Results of Experiment Two conducted in May.

Based on the above results, long-term experiments (six days) that did not take relativity effects into consideration were conducted in July. Figure 16 shows the whole of NICT's time comparison results. Synchronization error was controlled to within ± 0.3 ns except the period during which there were some problems in ground system communication, such as the transmission delay of time comparison results between main and sub TMSs.

Using these data, we calculated Overlapping Allan Deviation and show the results in Figure 17. Long-term stability at 100,000 s was 4.43×10^{-15} . This stability is comparable to that of hydrogen masers and is more than one order of magnitude higher than that of the initial goal (1×10^{-13}).

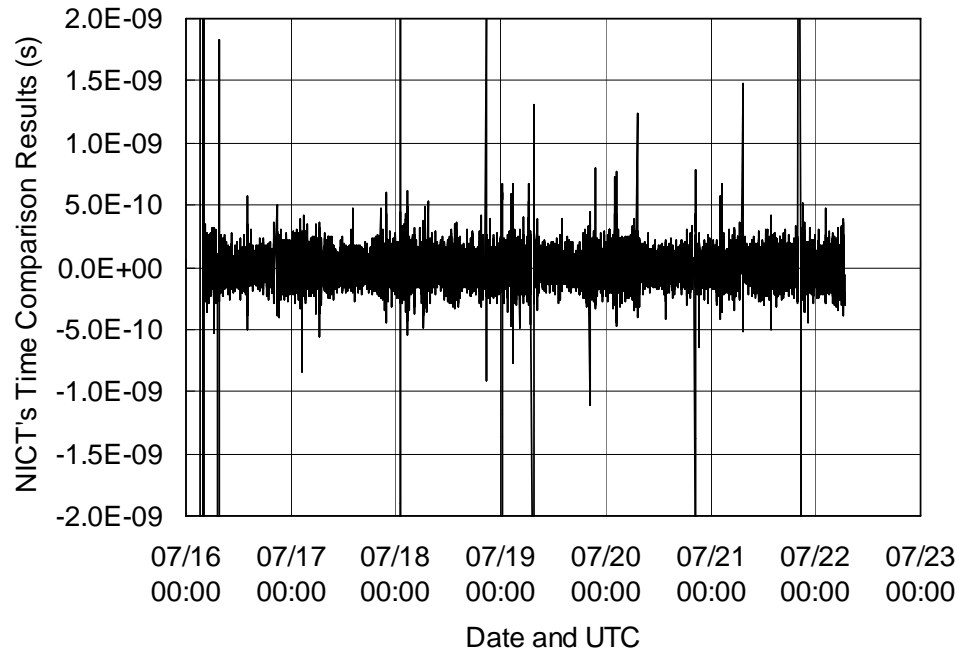


Figure 16. Results of Experiment Two conducted in July.

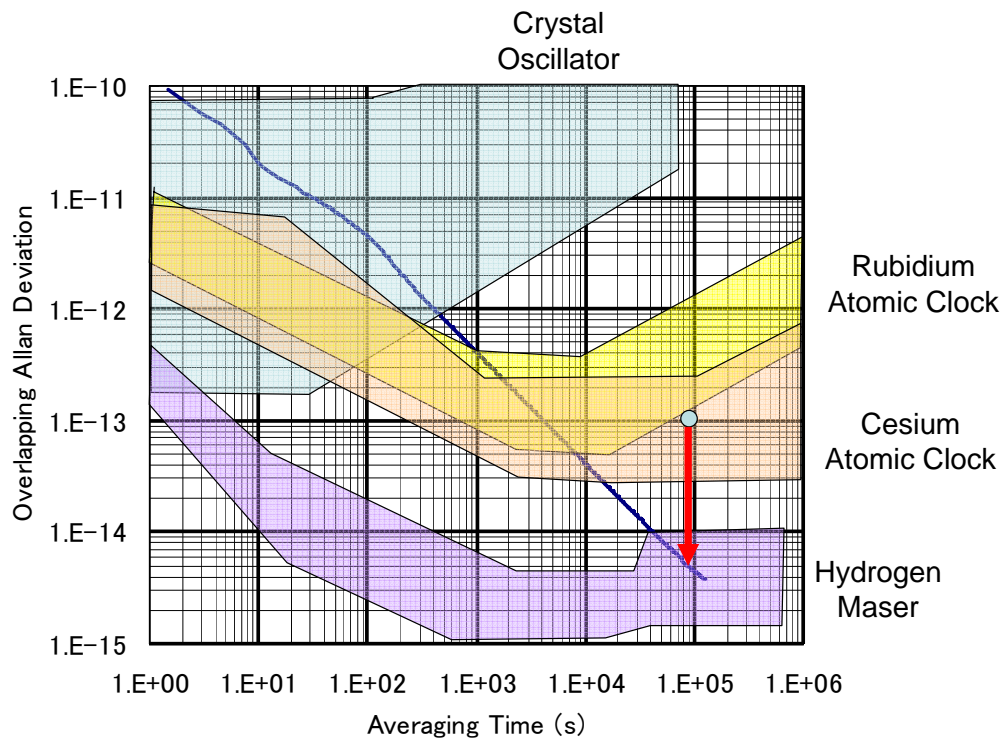


Figure 17. Overlapping Allan Deviation during Experiment Two execution in July.

Then, JAXA's clock offset during experiments was investigated. Figure 18 shows JAXA's clock offset and the relativity effects calculated with orbit estimation/forecast values. According to the experimental conditions, these two values should be identical except for some offset. However, the following are noted:

- (1) The vibration amplitude of JAXA's clock offset became smaller from approximately 0:00 of July 18.
- (2) JAXA's clock offset tended to show an upward direction.

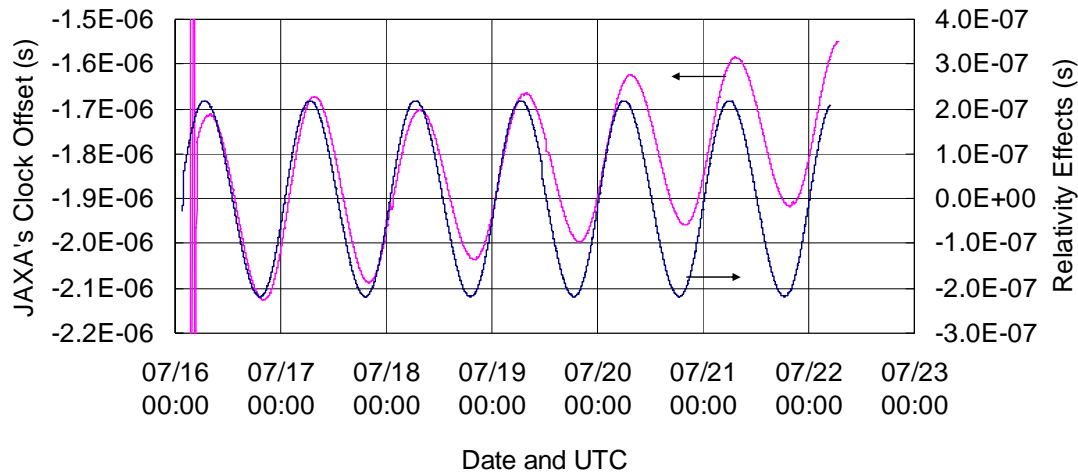


Figure 18. JAXA's clock offset and relativity effects during Experiment Two in July.

As regards (1), it is considered that geographical compensation (effects of movement of Michibiki and the earth during signal transmission) did not work at TMS from approximately 0:00 of July 18. As regards (2), NICT's time comparison results used by Experiment Two at Okinawa were calculated by adding the results of the time comparison between QZSSST1 and the hydrogen maser time at Okinawa TMS to the hydrogen maser time at Okinawa TMS. The reason was that the plus sign of the time comparison results was mistaken for a negative sign.

Using GPS and Michibiki's pseudoranges obtained by QZSSREC and RINEX files obtained by JAXA's QZ-Vision site [13], we calculated the independent positioning of QZSSREC's antenna and compared the case of the onboard rubidium atomic clock with the case of RESSOX for use of GPS alone and use of both GPS and Michibiki. In the calculation, only L1 C/A signals were used, ionospheric effect was ignored, and no weight was used for all satellites. The results are shown in Figs. 19 and 20. These results demonstrate that the performance of RESSOX is the same as or better than that of the onboard rubidium atomic clocks.

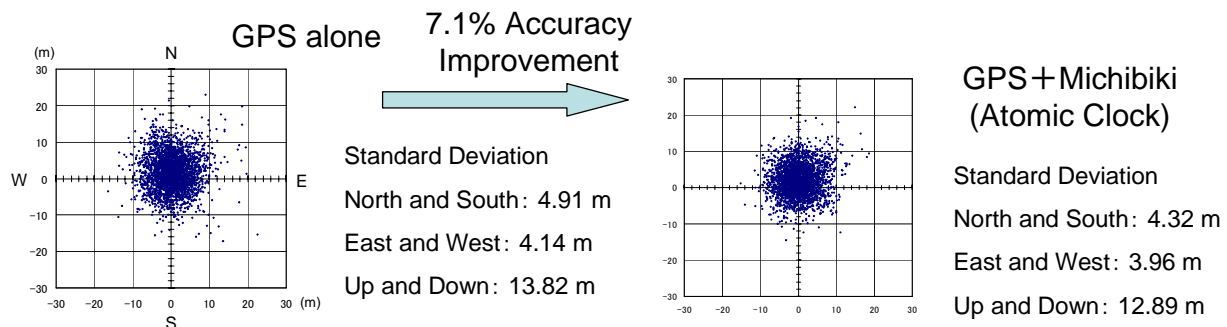


Figure 19. Positioning results at Okinawa using QZSSREC (2011/7/13 5:00 UTC - 7/14 5:00 UTC).

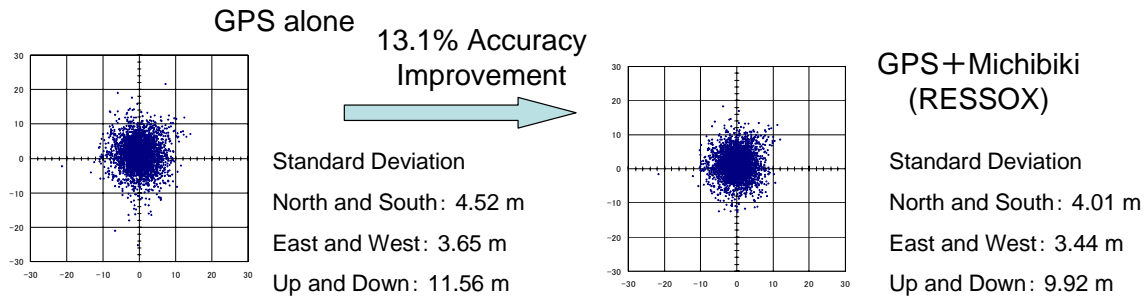


Figure 20. Positioning results at Okinawa using QZSSREC (2011/7/16 5:00 UTC - 7/17 5:00 UTC).

In September, we obtained the results of Experiment Two, as shown in Figure 21. The difference between JAXA's clock offset and relativity effects shown in Figure 18 was solved and we obtained the results shown in Figure 22. The difference between JAXA's clock offset and relativity effects was within 8 ns peak-to-peak except the offset of 1.127 μ s, as shown in Figure 23.

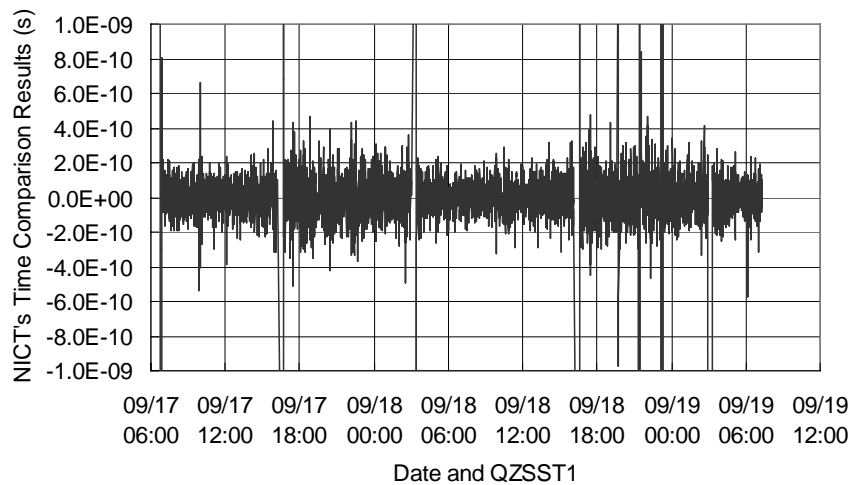


Figure 21. Results of Experiment Two conducted in September (without relativity effects).

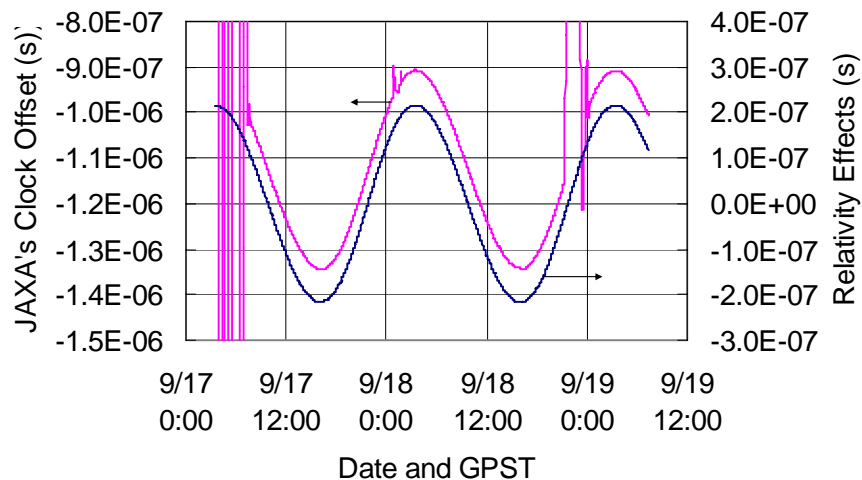


Figure 22. JAXA's clock offset and relativity effects during Experiment Two in September.

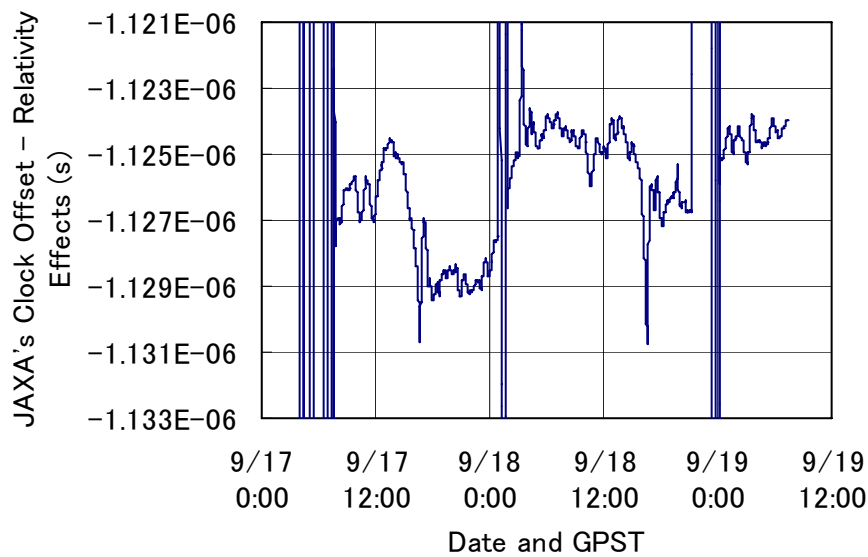


Figure 23. Difference between JAXA's clock offset and relativity effects during Experiment Two conducted in September.

Moreover, in September, relativity effects were taken into consideration in Experiment Two. In May, an unaccountable behaviour was noted, as shown in Figure 15. However, JAXA's clock offset was controlled to almost constant and the fluctuation was 8 ns peak-to-peak, as shown in Figure 24. JAXA's clock offset was approximately $-1.124 \mu\text{s}$, which was the difference between GPST and QZSST1, and 3 ns different from Figure 23. This fluctuation was almost the same as the case between the onboard rubidium atomic clock time calculated by the first-order approximation using af_0 and af_1 of the navigation messages and JAXA's clock offset, shown in Figure 25. Therefore, 8 ns is considered to be the limitation of JAXA's clock offset measurements.

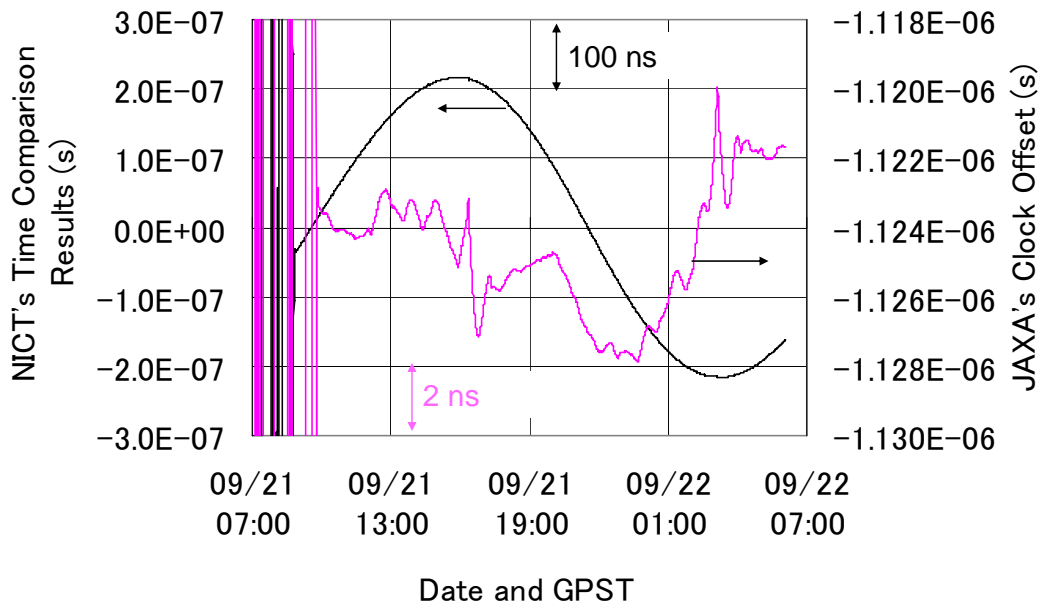


Figure 24. Results of Experiment Two conducted in September (with relativity effects).

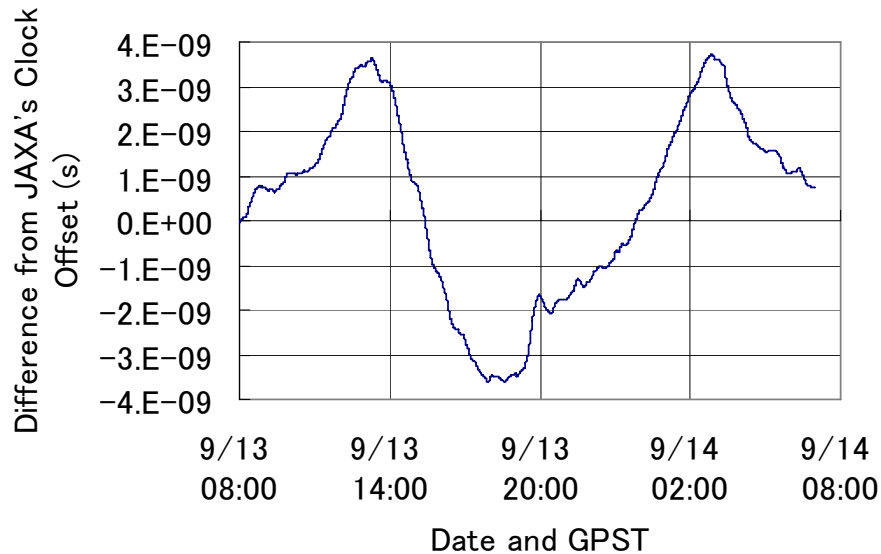


Figure 25. Fluctuation between onboard rubidium atomic clock time calculated by the first-order approximation using af0 and af1 of the navigation messages and JAXA's clock offset.

TECHNICAL ISSUES FOR ACTUAL OPERATION

We believe that Experiment Two may have greater applicability to actual operation instead of the onboard atomic clock. However, the following technical issues should be resolved:

- (1) In the case of signal attenuation due to rainfall or limitation of antenna direction control by typhoon, RESSOX is not available.
- (2) In the case of demonstration experiments, personnel are assigned to TMS and control is conducted by manual operation.
- (3) NICT time comparison results are indispensable and required all the time.

As the countermeasure for (1), switching over between more than two stations is indispensable. For (2), preparation of instruction manual, remote operation and supervision are required. For (3), an all-day automation system of NICT time comparison process should be developed.

V. CONCLUSIONS

This study is summarized as follows.

- (1) For the actual operation of RESSOX, Experiments One and Two were conducted. In Experiment One, discontinuities of three-minute orbit estimation/forecast values occurred every 30 s. In Experiment Two, approximately 9 to 12 s was required from the start of time comparison to the voltage command execution.
- (2) The schedule of demonstration experiments was described and the results of exploratory experiments in which VCOCXO was not controlled, Experiment One, and Experiment Two, were presented.

- (3) In the case of exploratory experiments, relativity effects and tropospheric delay accounted for the error of the results.
- (4) In Experiment One, the disagreement of signal transmission timing caused the error and control instability was observed in feedback control.
- (5) In Experiment Two, consideration of the relativity effects reduced the error of JAXA's clock offset to less than 8 ns peak-to-peak. This is the same as the results of the onboard atomic clock.
- (6) Three technical issues for actual operation were presented.

VI. ACKNOWLEDGMENT

This study was carried out as part of the "Basic Technology Development of Next-Generation Satellites" project promoted by the Ministry of Economics, Trade and Industry (METI) through the Institute for Unmanned Space Experiment Free Flyer (USEF). We also thank NICT, JAXA, and SED staff members who are involved in RESSOX experiments.

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